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Joint Command Support through Workspace Analysis, Design and Optimization

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Defence R&D Canada
Technical Report
DRDC Toronto TR 2009-100
October 2009

Canada

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Abstract

The current Canadian Forces (CF) transformation focuses on network enabled capabilities and promotes joint operations both within the CF and under a broad joint, inter-agency, multi-national, public (JIMP) paradigm. The past a few years have witnessed an increased demand on the science and technology (S&T) support for performing ergonomic analysis and workspace design for joint operations centres. A series of studies have been conducted from 2006 to 2008 in which workspace solutions were produced for three different joint command centres. In these studies, a new design process, Alternative method for Workspace ANalysis and Design (A-WAND), was proposed and then further developed. A-WAND is based on integrating and streamlining existing design procedures recommended in industrial standards and is tailored to support unique operational requirements of a CF joint command centre. In addition, it emphasizes the use of analytical methods and software tools that have been developed, and therefore possessed, by Defence Research and Development Canada (DRDC). This report describes A-WAND, documents the best design practises, and discusses future research and development (R&D) efforts that are needed to further advance DRDC's capability in this area.

Résumé

La transformation actuelle des Forces canadiennes (FC) porte sur des opérations facilitées par réseaux et fait la promotion des opérations interarmées à la fois au sein des FC et dans le cadre d'un paradigme interarmées, interorganisationnel, multinational et public (IIMP). Au cours des dernières années, on a constaté une augmentation de la demande sur le soutien des sciences et de la technologie (S & T) pour effectuer une analyse ergonomique et la conception de l'espace de travail pour les centres d'opérations interarmées. Une série d'études a été menée de 2006 et 2008 dans le cadre desquelles des solutions liées à l'espace de travail ont été mises au point pour trois centres de commandement interarmées. Dans ces études, un nouveau processus de conception, une méthode alternative pour l'analyse et la conception du milieu de travail (A-WAND), a été proposé puis développé de façon plus approfondie. L'A-WAND est fondée sur l'intégration et la simplification des procédures de conception existantes recommandées dans des normes industrielles et est adaptée pour soutenir les exigences opérationnelles uniques d'un centre de commandement interarmées des FC. De plus, elle met l'accent sur l'utilisation de méthodes analytiques et d'outils logiciels qui ont été mis au point et, par conséquent, ont été possédés par Recherche et développement pour la défense Canada (RDDC). Le présent rapport décrit l'A-WAND, rend compte des meilleures pratiques de conception et discute des futurs efforts de recherche et développement nécessaires pour faire progresser la capacité de RDDC dans ce domaine.

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Executive summary

Joint Command Support through Workspace Analysis, Design and Optimization:

Wenbi Wang; DRDC Toronto TR 2009-100; Defence R&D Canada – Toronto; October 2009.

Introduction or background:

The current Canadian Forces (CF) transformation focuses on network enabled capabilities and promotes joint operations both within the CF and under a broad joint, inter-agency, multi-national, public (JIMP) paradigm. The past a few years have witnessed an increased demand on Science and Technology (S&T) support for conducting ergonomic analysis and workspace designs for joint operations centres. Three studies have been conducted from 2006 to 2008 in which workspace solutions were created for a joint command centre of the Joint Task Force (East) (JTF(E)), an integrated command centre (ICC) and a JTF(Games) joint operations centre (GJOC) for the Vancouver 2010 Winter Olympic Games.

Results:

In these studies, a new workspace design process, Alternative method for Workspace ANalysis and Design (A-WAND), was created based on existing industrial standards. A-WAND consolidated two previously independent procedures for workstation and room layout designs and was tailored to support operational requirements of a CF joint command centre. A goal-based analytical method was used in conjunction with conventional task analysis for eliciting operators' requirements. Software toolkits were extensively used to support the design and evaluation. All three workspace solutions produced by this process were accepted by the CF client and later implemented.

Significance:

The aim of A-WAND was to create a Department of National Defence (DND) approach towards workspace analysis and design. The process emphasizes the use of methods and tools that are developed, and therefore possessed, by Defence Research and Development Canada (DRDC) Toronto. It differentiates workspace elements based on a consideration of the CF's operational tradition and its current technological capability. The streamlined process allows human factors specialists to respond to future workspace design requests in a timely manner.

Future plans:

A range of future Research and Development (R&D) activities are proposed at the end of the report. An R&D roadmap is suggested which includes the use of social network analysis for

communication modeling and the connection to human performance models for assessing the effectiveness of a workspace solution in dynamic operations.

Sommaire

Soutien du commandement interarmées au moyen de l'analyse, de la conception et de l'optimisation de l'espace de travail :

Wenbi Wang; RDDC Toronto TR 2009-100; R & D pour la défense Canada – Toronto; Octobre 2009.

Introduction ou contexte :

La transformation actuelle des Forces canadiennes (FC) porte sur des opérations facilitées par réseaux et fait la promotion des opérations interarmées à la fois au sein des FC et dans le cadre d'un paradigme interarmées, interorganisationnel, multinational et public (IIMP). Au cours des dernières années, on a constaté une augmentation de la demande sur le soutien des sciences et de la technologie (S & T) pour effectuer une analyse ergonomique et la conception de l'espace de travail pour les centres d'opérations interarmées. Trois études ont été menées de 2006 et 2008 dans le cadre desquelles des solutions liées à l'espace de travail ont été mises au point pour un centre de commandement interarmées de la Force opérationnelle interarmées (Est), un centre de commandement intégré (CCI) et un centre d'opérations interarmées pour les Jeux de la Force opérationnelle interarmées pour les Jeux olympiques d'hiver de 2010 à Vancouver.

Résultats :

Dans ces études, un nouveau processus de conception, une méthode alternative pour l'analyse et la conception du milieu de travail (A-WAND), a été créé selon des normes industrielles existantes. L'A-WAND a consolidé deux procédures indépendantes précédentes pour la conception de postes de travail et de l'aménagement de pièces et est adaptée pour soutenir les exigences opérationnelles uniques d'un centre de commandement interarmées des FC. Une méthode analytique axée sur un objectif a été utilisée en même temps qu'une analyse des tâches traditionnelles pour obtenir les exigences des opérateurs. Des trousses d'outils logiciels ont été abondamment utilisées afin de soutenir la conception et l'évaluation. Les trois solutions liées à l'espace de travail qui ont été mises au point dans le cadre de ce processus ont été acceptées par le client des FC, puis mises en œuvre.

Importance :

Le but de l'A-WAND consistait à créer une approche du MDN pour l'analyse et la conception de l'espace de travail. Le processus met l'accent sur l'utilisation de méthodes et d'outils qui ont été mis au point et, par conséquent, ont été possédés par RDDC Toronto. Elle différencie les éléments de l'espace de travail selon un examen de la tradition opérationnelle des FC et de ses capacités technologiques actuelles. Le processus simplifié permet aux spécialistes en ergonomie de répondre rapidement aux demandes futures concernant la conception de l'espace de travail.

Plans futurs :

Une gamme d’activités futures de recherche et développement (R & D) est proposée à la fin du rapport. On propose une feuille de route de la R & D qui comprend le recours à l’analyse de réseaux sociaux pour la modélisation des communications et la liaison aux modèles de performance humaine en vue d’évaluer l’efficacité d’une solution relative à l’espace de travail dans le cadre d’opérations dynamiques.

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Acknowledgements

All three workspace design studies were led by DRDC Toronto and supported by Esterline | CMC electronics. Sharon McFadden, Walter Dyck, and Ron Funk have provided invaluable S&T support to these studies.

1 Introduction

The current Canadian Forces (CF) transformation focuses on network-enabled capabilities and promotes joint operations both within the CF and under a broad joint, inter-agency, multi-national, public (JIMP) paradigm. One example is the support of major events in which the CF, as a key player, collaborates with other government departments and agencies. Under this context, the past several years have witnessed an increased demand on Science and Technology (S&T) support for conducting ergonomic analysis and workspace designs for joint operations centres. From a conventional CF operations centre to a joint command centre, Defence Research and Development Canada (DRDC) has recently led three studies and explored the use of a range of analytical and modelling techniques for supporting this type of endeavour. The workspace solutions produced in each study, as well as the raw data, were recorded in the respective contract reports (Coates & Perlin, 2006; Coates, Perlin, & Stewart, 2009; Coates & Perlin, 2009). The purpose of this technical report is to describe the design process, document the best design practises, and highlight future Research and Development (R&D) efforts needed to further advance DRDC's capability in this area.

This report consists of five sections. Section 1 summarises the operational requirements of a military joint command centre and describes the scope of its workspace design. Section 2 explains two generic workspace design procedures that are recommended by existing industrial standards. Section 3 provides an overview of three recent design projects and summarises the key design considerations. Section 4 describes a tailored design process, Alternative method for Workspace ANalysis and Design (A-WAND). A-WAND was created in response to the unique operational requirements of a military command centre. It uses analytical methods and design tools that are accessible to DRDC and streamlines design procedures to accommodate practical constraints encountered in such projects. Section 5 provides a critique of this new design process and suggests a future R&D roadmap.

1.1 Command Centre and the Scope of its Design

A command centre is often regarded as a facility where centralized commands are produced. Its effective operation depends on many functions, including information fusion, situational awareness, decision-making, and execution monitoring (Essens, Post, & Rasker, 2000). Command orders are the final products of these functions, and their generation depends on the collaborative work from a group of operators, including the commanders. Although the term *command centre* has a root in military operations, this concept has been widely applied in many non-military domains. In fact, wherever centralised information fusion and decision-making are needed, a command centre of some sort can be created. Examples can be found from a nuclear power plant control room to an emergency response dispatching unit.

The effective operation of such a facility, especially the successful delivery of its high-level product (i.e., decisions or command orders), typically depends on three elements: information, resources, and communication.

A command centre is a conduit for receiving, analyzing, and synthesizing information. Such information comes from a wide range of sources, including machine sensors (as in a nuclear power plant), first responders (e.g., emergency response unit), and military intelligence. Operations in a command centre often consist of consolidating and de-conflicting the heterogeneous sources of information, using such information to diagnose and prioritize critical incidents. A measurable outcome is the correct situational awareness shared among the operators and the decision-makers (e.g., commanders).

The second aspect is the deployment and tracking of resources, including personnel and equipment. Their allocation depends on the nature of an incident and its criticalness. Successful command orders are often judged based on an appropriate and effective utilization of resources.

If information and resources are considered as the tangible functions of a command centre's operation, then communication is a virtual medium that makes these functions possible. Indeed, one important motivation behind the creation of a centralised facility is to enhance communication. The assumption is that a team will coordinate and collaborate better if team members are co-located in the same room. Of course, this assumption is only valid if the command centre is appropriately designed.

The scope of a command centre's design has many facets, and workspace configuration is only one. A successful workspace setup depends on other aspects of the design, including the creation of its Concept of Operations (CONOPS), the setup of its organizational structure, the definition of operator roles and responsibilities, and the identification of technological support.

The CONOPS of a joint command centre is a guiding document that describes the key aspects of a centre's operation (Smart Risk Control, 2007). It typically explains a command centre's mission objectives, operators' roles and responsibilities, their operational requirements, and sometimes mission scenarios. Such information dictates how a centre is operated, which in turn provides the highest level guiding principles for a command centre's design. The mission objectives included in a CONOPS serve as the ultimate criteria for assessing a command centre's operational effectiveness.

As an organization, a command centre consists of a team of operators, each with a specific role and responsibility. An early task in a workspace analysis is to decide who should be allocated in the centre and how a team of operators should be structured together. A common mistake is to include too many operators, which can lead to increased congestion and interference. Network technologies have greatly reduced the barrier for remote collaboration. As a result, designers need to justify not only each operator's role in supporting the overall command centre's operation, but also the need for that operator's space allocation within the centre.

The organizational structure affects how operators interact and how information is disseminated. For example, a flat, shallow structure allows information and orders to pass quickly along the vertical chain of command, whereas a narrow and deep format supports layered quality control. The selection of a particular organizational structure depends both on the nature of operation and the type of tasks that are expected to be handled (Perrow, 1967).

Modern command centres rely increasingly on networked computers and large screen displays for presenting and sharing information. Technology has greatly enhanced one's ability to analyze and

distribute information. It has also changed how operators interact with each other (Gouin, 2007). From a workspace designer's perspective, it is important to understand the impact of technology on social interaction and adopt adequate technology to facilitate desirable behaviour.

Workspace solutions can be created only after the above issues have been addressed. Typically, workspace designs consider the personal workstations (i.e., consoles), the room layout, and the environmental conditions. This is an area where the human factors specialists are frequently involved and ergonomic principles are applied.

1.2 Operational Characteristics of Joint Command Centres

A military command centre differs in many ways from a civilian one. The differences have implications on workspace choices. This subsection summarises the major operational characteristics of a joint command centre that were identified in the past studies (Coates & Perlin, 2006; Coates, Perlin, & Stewart, 2009; Coates & Perlin, 2009). They will justify the design process adopted in these studies.

1. The CONOPS of a command centre within each branch of the CF (e.g., land, air, sea) is commonly well-documented, but the same can not be said for joint command centres where an integrated force is applied. Therefore, depending on the type of command centres, the work involved in CONOPS generation ranges from a simple document review to an extensive design and development effort.

2. The personnel roles and responsibilities assignments for a conventional CF command centre are clearly defined. For example, it is always led by a commander who is supported by subordinate staff from several functional areas (e.g., intelligence, planning, operations, and logistics). Its operations are often divided into 'current ops' and 'future ops', depending on an operation's time horizon. However, in a joint command centre where multiple agencies are involved, the conventional CF role assignments may not be sufficient. Ambiguity may arise during cross-agency collaboration, and operators' roles and responsibilities need to be further clarified. This issue becomes more salient when non-Department of National Defence (DND) entities are included in the command centre.

3. A military command centre follows the CF's operational traditions. It is therefore important to adopt an evolutionary approach toward workspace design. This approach allows its staff members to take advantage of the trainings that they have previously received. However, when the design focuses on a joint command centre that consists of non-DND players, the standard operating procedures may not be well established.

4. A CF command centre often serves as a module in a larger command and control infrastructure, either at a national or international level. As a result, the external communication plays an important role in its operation and a standardised interfacing protocol among these interconnected centres should be followed.

5. A CF command centre deals with a wide variety of incidents, including threats that have severe consequences. As a key facility, command centres can become a target for disruptive activities. Because the cost of error or failure is so high, it is important to

consider backup capabilities in its design. Contingency operational plans should be put into place and adequate redundant capabilities considered.

6. Given that a CF command centre has access to information from a large number of sources, information fusion is particularly important. A joint command centre typically has intelligence inputs from land, air, and sea, and maintains a common operating picture (COP) that depicts friendly force (blue picture), enemy force (red picture), neutral force (white picture), and weather information (brown picture). How to integrate these tactical pictures requires inputs from both Information Technology (IT) professionals (e.g., hardware and software requirements) and human factors specialists (e.g., cognitive constraints).

7. Any command centre is expected to handle non-routine operational demands. However, this is particularly important for a military command centre, since an element of surprise is deeply entrenched in military doctrines. From a workspace designer's perspective, this requirement translates into a solution that emphasizes flexibility and reconfigurability.

8. A military command centre handles sensitive data. Security is always a high priority. This has implications for workspace design. For example, the networked computers are one of the primary means for information collation, communication, command distribution, as well as action logging. There often exist both an unclassified and a classified network in a command centre. An operator may need to have multiple computers on her desk, each running on a particular network. Because of security regulations, there are specific restrictions on the minimal proximity between classified and un-classified computers, which must be reflected in the workspace design.

9. Communication within a command centre takes various forms. While conventional means like direct conversation, telephone, fax, email, are still widely used, recent IT advances enable an increased use of networked chat tools and electronic situational boards for maintaining situational awareness. The setup of large shared displays has become an important topic in workspace analysis.

10. A command centre often operates at a 24/7 capacity, with operators working on a shift schedule. It is important to provide a comfortable working environment to sustain potential long operation hours. The configuration of personal workstations should consider the posture and anthropometric characteristics of an operator. Although this is generally applicable to any kind of control room, it is a requirement frequently highlighted by the CF client.

11. The inclusion of multiple agencies and departments in a joint command centre raises compatibility issues for both equipment facilities and operational cultures. The use of different network and software tools increases the difficulty in electronic information exchange. On a more subtle level, the cultural difference between agencies (e.g., DND and non-DND entities) has an impact on communication and information sharing. These factors all influence workspace choices.

Operations carried out in a military command centre differ from those of a non-military control room. The aforementioned characteristics require analysts to focus with varying levels of effort

on different workspace elements. They also affect the selection of methods and tools for supporting the design. Over the past decade, DRDC has developed a battery of analytical methods and software tools to support ergonomic analysis of a workspace (e.g., Hendy, 1989; Hendy, Edwards, & Beevis, 2000). In three recent studies, a combination of these methods and software aids were incorporated into a new workspace design process. The following sections will document both this design process and the application of specific design methods and tools.

1.3 Relationship to Other Documents

The following documents are directly relevant to this report:

(1) Coates, C., & Perlin, M. (2006). Ergonomic and layout analysis of the Joint Task Force East (JTF(East)) command center, Contract report CMC document 1000-1383, DRDC Toronto CR 2006-241.
(2) Coates, C., Perlin, M., & Stewart, A. (2009). Ergonomic and layout analysis of the integrated command centre (ICC), Contract report, DRDC Toronto CR 2009-029.
(3) Coates, C., & Perlin, M. (2009). Ergonomic and layout analysis of the Joint Task Force (Games) operations Centre (GJOC), Contract report, DRDC Toronto CR 2009-028.

They are contract reports produced for three separate workspace design studies: for JTF(East), ICC, and GJOC respectively. While the current report focuses on the design process and its selection of specific methods and tools, the readers are referred to these original contract reports for detailed design data and workspace solutions.

2 Generic Workspace Design Procedures

The workspace in a command centre refers to the entire volume of space that is allocated to all operators. On an individual level, such space consists of areas around a personal workstation (i.e., a console). On a group level, the workspace refers mainly to the adjacency among workstations and shared facilities. The objective of workspace design is to provide a healthy and comfortable working environment that enables operators to carry out their work effectively and achieve the operational goals of the command centre.

A list of industrial standards provides guidelines that are relevant to a joint command centre's setup. Some of these standards consist of specifications for configuring control centres or office spaces, while others target particular design areas that are relevant to workspace setup. The following list represents the International Organization for Standardization (ISO) findings obtained from a literature review.

- ISO 11064: 2000, *Ergonomic design of control centres*.
- ISO 9241-3: 1993, *Ergonomic requirements for office work with visual display terminals*.
- ISO 6385: 2004, *Ergonomic principles in the design of work systems*.
- ISO 7250: 1996, *Basic human body measurements for technological design*.
- ISO 11428: 1996, *Ergonomics – visual danger signals – general requirements, design and testing*.
- ISO 9355-2: 1999, *Ergonomic requirements for the design of displays and control actuators*.
- ISO 13407: 1999, *Human-centred design processes for interactive systems*.
- ISO 13731: 2001, *Ergonomics of the thermal environment – vocabulary and symbols*.

Many of these standards were referred to and applied in the recent studies (hereafter referred to as the Joint Command Workspace Analysis (JCWA) studies) (Coates & Perlin, 2006; Coates, Perlin, & Stewart, 2009; Coates & Perlin, 2009). Among them, ISO 11064 has had the greatest influence. With an aim to support workspace designs for a wide range of control centres, ISO 11064 provides a comprehensive solution which can be applied to a military command centre. In particular, the design process that was followed was created on the basis of two procedures suggested by ISO 11064. A brief description of ISO 11064 and the two procedures is provided in this section.

2.1 ISO 11064: An Overview

ISO 11064 specifies ergonomic principles, recommendations and requirements for the design and evaluation of workstations and control rooms. It covers a wide spectrum of design topics with a general emphasis on dimensions and layouts. The ergonomic principles typically focus on operators' interaction with the equipment and other operators, and they support the achievement of performance objectives set for a control centre. Operational effectiveness, operator well-being, health and safety are key criteria used for evaluating the success of a workspace solution.

ISO 11064 has eight sections:

1. Principles for the design of control centres,
2. Principles for the arrangement of control suites,
3. Control room layout,
4. Layout and dimensions of workstations,
5. Displays and controls,
6. Environmental requirements for control rooms,
7. Principles for the evaluation of control centres,
8. Ergonomic requirements for specific applications.

While all are relevant to command centre designs, workstation setup, room layout, and environmental requirements are three topics that provided the most useful information for the JCWA studies.

2.2 Workstation Design

The design of a workstation, or work console, includes consideration of furniture, equipment, and required working areas based on an operator's work needs. The analysis focuses on an individual's interaction with equipment and is performed when specialised consoles are used. It considers anthropometric data, operators' work posture, equipment interfaces, and the interaction modality. An important design criterion is to ensure the workstation can be effectively used by a majority of operators from the potential user population. The following list shows the scope of analysis and issues considered:

- User population (male, female, disabled) and the associated anthropometric data;
- Work posture (sit, stand, or combination);
- Interaction modality (visual or auditory displays);
- Visual perception (line-of-sight, cone of fixations, visual angle, field of vision, near point, viewing distance);
- Display and control (legibility, reach envelope, task zone);
- Dimensions (thigh clearance, eye height, elbow height, feet clearance, etc.).

In ISO 11064, the design guidelines deal primarily with workstations where operators interact with visual displays in a seated position. A generic procedure for workstation analysis and design is suggested, as shown in Figure 1.

The procedure starts with the identification of operational objectives for each operator. A task analysis is recommended to capture all tasks that an operator needs to perform at their workstation. The task information is critical to the analysis, because it is used for determining control functions, information requirements, and specifying equipment requirement for each operator.

The next step is to obtain anthropometric data representative of the user population. The data allow analysts to calculate dimensional limits for the workstation based on the operator's anticipated working posture. Given the type of workstations ISO 11064 focuses on, the relevant

design principles consider factors like visual perception (e.g., line of sight, view-over height, field of view), control motor (e.g., reach zone), and comfort space (thigh clearance, knee/foot room, etc).

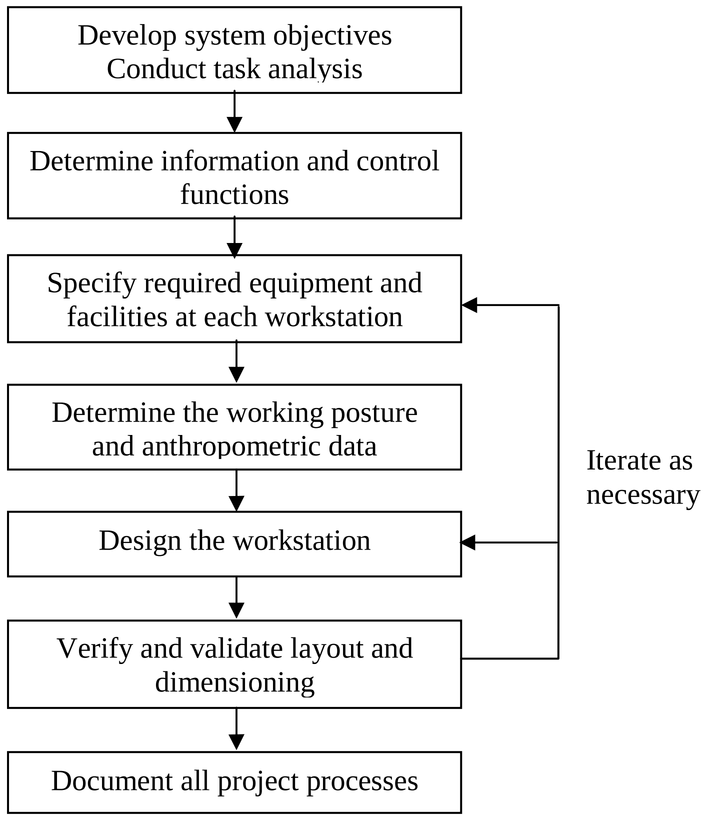

Figure 1*. A generic process for workstation design, simplified from ISO 11064.*

These dimensional limits ensure that the design considers the full height and size range of the potential user. A common design heuristic is to allow operators have an unobstructed view to all relevant sources of information, and conduct tasks in expected postures for a designated period of time. To achieve this objective, a series of ergonomic principles is applied. For example, the height of a console should allow the smallest operator to see over the top of computer monitors (if such behaviour is expected by the work). The clearance underneath the work surface should allow for the tallest operator to sit comfortably. An element of flexibility should be built in the design to enable a re-positioning of movable equipment (e.g., telephones, keyboards) and writing areas, allowing operators to change postures during their shift, minimizing fatigue.

Once a workstation design is completed, it is subject to verification and validation. This takes place at various stages and in various forms. An initial evaluation can be conducted on design blueprints using subjective methods and a comprehensive evaluation can be performed on mock-up prototypes using more objective performance measures. Regardless of the form, direct user involvement is key. User feedback is passed to the designers for adjustment. The entire process is

iterative. Note that the *user* refers to not only the operators, but also supporting staff. An important aspect of evaluation is the consideration of maintenance requirements. Concerns like equipment installation and removal should be considered in the design as well.

The last step is project documentation, which includes not only the finalised workstation solutions, but also design constraints and assumptions, alternative considerations, and compromises made in the design. The complete record enhances a solution's traceability, allows an analyst to troubleshoot the design at a later time, and contributes to future design projects.

2.3 Room Layout

Once the design of individual workstations has been finished, the next design task is to position them on a control room floor. The room layout considers both individual workstations and shared facilities. Its design focuses on the interaction among operators, particularly their communication needs. Frequently asked questions include: "Who should be positioned close to each other?" and "How will that affect overall collaboration effectiveness within the command centre?"

The physical proximity among workstations and shared equipment is a key consideration. A desired layout should support communication and avoid crowding the centre by creating short separations between adjacent operators. In addition, the layout analysis should consider architectural factors (e.g., entrances and exits) and safety features (e.g., hand rails).

Figure 2 shows a general procedure recommended by ISO 11064 for designing the layout of a control room. It starts with an identification of the physical space for the control room. This includes its dimensions, useable and un-usable areas, physical constraints like pillars or risers, and other architectural features, like windows, entrances, and exits.

A functional layout is produced by dividing the physical space into functional areas. Within each area, the primary workstations (e.g., those always staffed in an operation) and main off-workstation displays (e.g., shared displays) are localised, followed by secondary workstations and other ancillary equipment.

More than one layout solution is often produced. Solutions are verified against operational requirements and later tested in full-scale mock-ups, if necessary. Sometimes, a matrix of functional links within the control room is produced to examine the pros and cons of each option. Similar to workstation designs, direct user involvement is key for layout validation (including operators and support staff). In some cases, a risk and cost analysis is also performed.

The procedure is completed with a full documentation of the entire design effort. The pros and cons of each layout solution are recorded and submitted to the decision-maker to justify the final workspace decision.

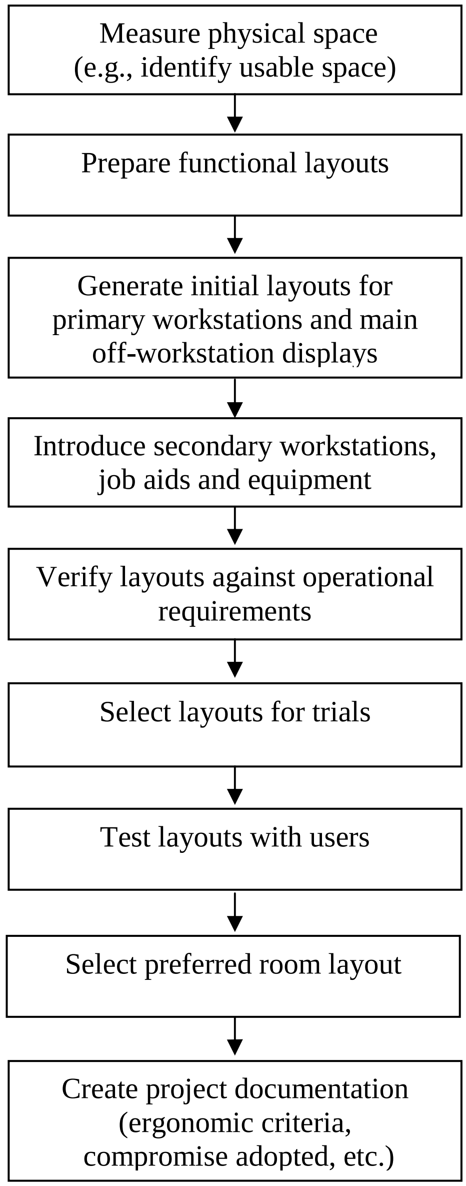

Figure 2. *A generic procedure for control room layout, simplified from ISO 11064.*

2.4 Environmental Specifications

The third aspect of ergonomic analysis deals with environmental requirements. These requirements affect both work efficiency and comfort level. In ISO 11064, the environmental requirements cover seven areas, including thermal environment, air quality, lighting environment, acoustic environment, vibration, aesthetics and interior design. These requirements are applicable to most types of control centres and their design guidelines are generated based on operators' task

demands and comfort requirement. It is useful to note that the demands of different environmental features sometimes conflict, and a trade-off assessment is needed based on operational priority.

A generic procedure for properly specifying these environmental factors is provided in ISO 11064. This procedure was followed in the recent studies. However, it is not further described here, since no changes were made to this procedure in these studies. Readers are referred to ISO 11064 for more information.

3 Three Recent Design Projects

Between 2006 and 2008, DRDC Toronto led three studies in support of ergonomic analysis and design for CF joint command centres. These studies resembled one another in their operational requirements and design constraints. Based on the similarities, a new workspace design process, A-WAND, was created. A recap of these studies, particularly a review of common design considerations, is provided in this section. Due to the sensitivity of data, design details are omitted in this report.

3.1 Joint Command Centre for Joint Task Force (East)

Joint Task Force East (JTF(E)) is responsible for domestic CF operations in the province of Quebec. Its joint command centre (JCC) enables the JTF(E) Commander to maintain situational awareness for effective decision making in support of CF operations within its dedicated area of operations.

In 2006, JTF(E) undertook a physical and a functional re-engineering of its JCC. The objectives were to use its existing space more efficiently, facilitate inter-member information exchange and optimize human computer interaction. More specifically, it sought recommendations in the following three areas:

- Produce a suitable organization of personnel and an effective workspace layout;
- Specify individual workstation characteristics, including the layout of computers and related peripheral equipment;
- Configure a large screen shared display within JCC.

The request was sent to DRDC Toronto and a study was conducted. There was limited time to complete the project. The entire study, from data collection to design validation, had to be completed within six weeks. In response, the project team decided to consolidate the workstation and layout design procedures into an integrated process, i.e., A-WAND. One of the key enablers was the use of a hierarchical goal analysis (Chow, Kobierski, Coates, & Crebolder, 2006), in conjunction with conventional task analysis, to capture user requirements. Specialised layout software, LOCATE (Edwards, 1999), was used in the design. The combination of streamlined process and computer software support helped ensure that the project was completed on time. The workspace solutions were accepted by the client and later adopted in the command centre.

3.2 Integrated Command Centre (ICC)

The mission of the Integrated Command Centre (ICC) is to facilitate an effective and efficient coordination of security assets to ensure the safety of athletes and the public during the Vancouver 2010 Winter Olympics. The ICC includes multiple levels of command centres. A Theatre Command Centre (TCC) is situated at the top level and is responsible for all security operations within the designated theatre of operations. It is supported by a number of area and venue command centres, including:

- Air Security Operations Coordination Centre (ASOCC);
- Olympic Marine Operations Centre (OMOC);
- Vancouver Area Command Centre (VACC);
- Whistler Area Command Centre (WACC); and
- Joint Task Force (Games) Joint Operations Centre (GJOC).

In May 2008, DRDC Toronto initiated two studies to support the workspace design of the ICC: one for GJOC and the other for the rest of the ICC.

The ICC study involved the workspace design of five component command centres, which varied in physical location, size, and the scope of operations. The ICC staff members came from several departments and agencies. At the time the study was conducted, both the ICC CONOPS and Standard Operating Procedures (SOPs) were not fully established. This affected the choice of analysis and design methods. The lack of understanding of inter-departmental collaboration made a task analysis based approach (e.g., as suggested by ISO 11064) more error-prone. Following the experience in the previous JTF(E) study, hierarchical goal analysis (HGA) was used instead. Outputs from HGA were linked to operator tasks, wherever possible, and such information was then applied in both workstation and layout designs. Details of the analysis are explained in Section 4.

The Virtual Navigation and Collaborative Experimentation Platform (VNCEP) was used in the layout design. The workspace solutions were later implemented in ICC and were tested subsequently in two live exercises, EX Bronze and EX Silver. Positive user feedback was received from both exercises.

3.3 JTF(Games) Joint Operations Centre (GJOC)

As one of the component command centres inside ICC, GJOC is unique since it is staffed entirely by CF members. It serves as a conduit in ICC for accessing military intelligence and directing certain CF assets. Its operation is similar to that of a CF operations centre. Within ICC, GJOC interact primarily with TCC. At the same time, GJOC is situated within the CF command and control infrastructure and needs to interact with other CF entities as well. One of the challenges in this study was to figure out its interaction with other external entities.

The same analysis and design procedures used for ICC were used for this study. HGA was used for capturing operator requirements. Due to the similarity in operational requirements, HGA output, particularly the high level goals, was found to be robust enough to be transferred from one CF command centre to another. In practice, the goal hierarchy from the JTF(E) study was used as a baseline template for GJOC. This reduced the effort in data collection and allowed analysts to use the limited Subject Matter Expert (SME) time for addressing design and validation issues.

The layout solutions were generated in VNCEP and a multi-tiered hierarchical layout was adopted. This solution facilitated sub-team discussions and maximized the accessibility to operators from key roles (e.g., the senior watch officer) in GJOC.

The workspace solution was implemented and has been validated in two recent exercises. In both cases, minor adjustments were made on the layout and operators' feedback was generally satisfactory.

3.4 Key Design Considerations

While the scope of a joint command centre's design covered by all elements discussed in Section 2, the CF clients' emphasis on these elements differed from that of a non-military control room. This was consistently observed in all three studies. Because the analysts understood these differences, they could adjust the design process accordingly and allocate more resources to elements that the clients regarded as higher priority. This subsection describes the key design areas identified in three recent studies.

3.4.1 Workstation configuration

The term *workstation* refers to all equipment such as computers, communication devices and furniture at which control and monitoring functions are conducted. In a joint command centre, the workstations are commonly designed for seated operators. A similar configuration was adopted across three studies for all operators in the same command centre. This baseline workstation consists of an office desk, a height-adjustable chair, one or two computer systems with dual-monitors, and a regular telephone. Where access to additional equipment (e.g., secure phones) was needed, adjustment was made to this baseline.

The rationale for creating the baseline setup is threefold: first, it emphasizes the use of generic equipment, which is cost-effective compared to specialised hardware; second, it simplifies the design by applying the same configuration to all operators; finally, it creates a command centre that is highly reconfigurable. This is especially important for command centres where CONOPS or SOPs have not been finalised while the workspace design is conducted (e.g., the ICC).

In all three studies, the workstation design focused on the baseline configuration, particularly its anthropometric dimensions. Key areas of analysis included view-over height, work surface height, thigh clearance, knee room, foot room, and eye point. Figure 3 illustrates measurements that guide the design. An analysis of possible postures was also conducted to compare, for example, 'bent forward' and 'reclined' positions and their impact on the visual display setup, as shown in Figure 4.

The base anthropometric data were obtained from the Canadian Land Forces survey (Chamberland et al., 1998). All designs accommodated operators of various sizes ranging from the 5^{th} percentile female to the 95^{th} percentile male.

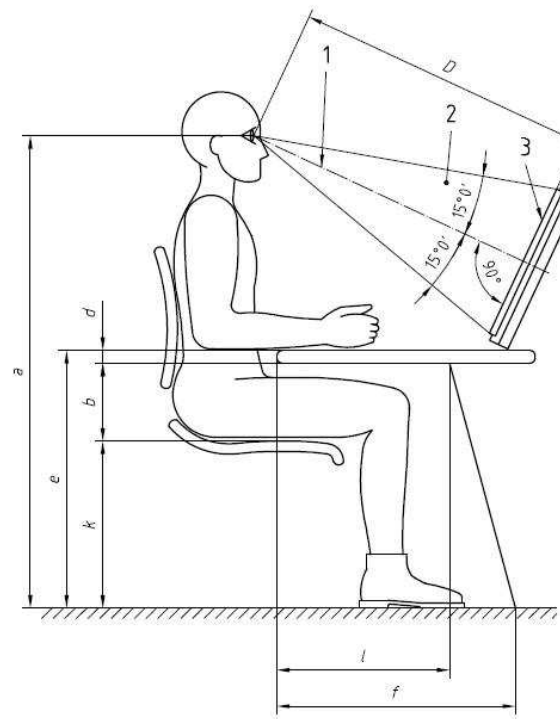

***Figure 3**. Key anthropometric dimensions of a seated control workstation (adopted from ISO 11064).*

The use of a baseline configuration reduces the design effort. Technology plays a critical role, networked computers and collaborative applications are two main enablers. The use of thin client (e.g., web-browser based) applications and Voice-over-IP (VOIP) technology allow all personal data, including the telephone number and software applications, to be highly portable. This has reduced the workstation design effort and makes it possible to create a highly reconfigurable and expandable solution.

3.4.2 Room layout

Compared with workstation setup, the design of a room layout is more complex. There are a number of layout requirements that are unique to a joint command centre.

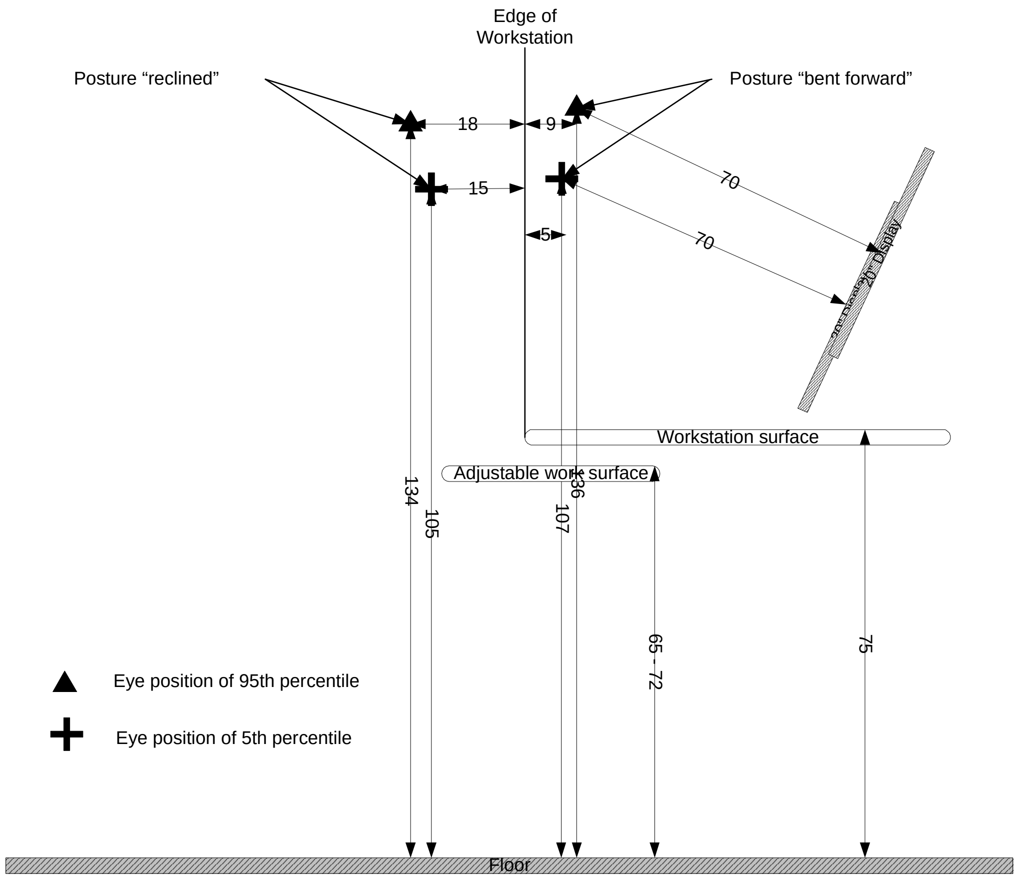

***Figure 4**. An analysis of the impact of posture on visual display setup (Adopted from Coates & Perlin (2006)).*

One requirement is the protection of sensitive information. This was highlighted in the design of the ICC where operators from multiple governmental departments and agencies worked together. Although all operators possessed adequate clearance to work inside the ICC, there were cases where certain intelligence information was meant to be shared only within a sub-group within the command centre. Such consideration was factored in the layout design. The challenge is how to create a layout that supports inter-operator collaboration, while at the same time restricting access to certain (visual and/or auditory) information for a particular group. The solution is some form of physical barrier, selection of which depends on the sensitivity level of information that needs to be protected. For example, half walls and elevated floors are used for discouraging physical access to certain areas; transparent partitions protect information distributed auditorily but still allow visual communication from two sides of the wall; a separate room is used in case where the highest level of protection is needed. A top secret (TS) break-out room was created and accredited in the ICC for this purpose.

Another requirement revealed in three studies is the operational traditions of different agencies. Military operations differ from civilian ones in many aspects, whose impact is manifested in the setup of the operations centres. For example, a CF operations centre is often organized in a

hierarchical format, corresponding to the chain of command, while a civilian emergency response unit frequently uses a round-table form that allows an equal say among all stakeholders. Since a joint command centre could involve operators from many agencies, it is deemed important to consider the operational traditions, including layout formats, of these agencies and create a workspace solution that takes advantage of operators' past training.

In recent studies, a review of existing layout schemes was conducted. In particular, three types of layouts were identified and examined in detail:

1. A *board room* setup in which operators sit around a common desk. This layout has been adopted in emergency response units before and has been proved effective for a small team of decision-makers. Sitting around the same table is commonly believed to support direct face-to-face communication and enhance collaboration efficiency, however, it is not as effective for a large team, or one that has to deal with multiple event threads (Rappoport, Cushman, & Daroff, 1992). With the addition of equipment like computers and monitors, the advantage of this solution also diminishes.

2. A *mission control room* setup which involves rows of operators facing the same shared large-screen displays. This solution is hierarchical, typically structured based on a chain of command, with supervising positions at the back rows. The biggest strength of this solution is that it supports shared situational awareness since all operators are facing the same direction, according to which common displays can be set up to share information. This layout also accommodates a large team of operators. It has been frequently used by both military and civilian operations centres. One disadvantage is that the operators' physical accessibility is poor. If operators need to get up and walk around, this solution becomes less desirable.

3. A *pod-based* setup which is sometimes also referred to as a marketplace configuration. This layout involves the setup of many smaller pods within a command centre, with each pod representing certain functional areas. Within each pod, either a mini board room or a mission control arrangement can be setup depending on whether intra-pod communication or the access to common displays is more important. Between the pods, sufficient spaces are created for passage ways and the proximity among pods is determined by the characteristics of inter-pod communication links (e.g., types, frequency and priority). This layout solution reflects a decentralised approach and is particularly effective for improving an operator's physical accessibility. The design can accommodate a large team of operators and can also be expanded easily. The setup of pods based on their function supports the parallel processing of multiple threads of events. The pod-based layout was found to be particularly useful for large joint command centres. Its expandability and flexibility were helpful in the design of the ICC where uncertainties about its operational requirements existed during the design of the layout.

3.4.3 Off-workstation displays

The off-workstation displays are common displays shared among a team of operators and often presented in a form of large group displays or wall displays. They are set up to either support shared situational awareness or collaborative work and are widely used in joint command centres. As revealed in the recent studies, the CF clients' requirements of off-workstation displays have

generally focused on two main aspects: display characteristics and collaborative work requirements.

Display characteristics refer to the physical attributes of a display, such as its size, luminance level, resolution, and allowable viewing angles. These physical attributes have a strong influence on a display's legibility, and are largely determined by the different display technologies. In the JTF(E) study, for example, the comparison generally focused on various projection technologies and Liquid Crystal displays (LCD) (Coates & Perlin, 2006). Cost was often also factored in the selection process.

During workspace design, the decision on off-workstation displays is made in conjunction with other considerations such as the size of a room, ambient lighting, and the type of information (textual or graphical) that needs to be presented. Such requirements are then linked to each operator's posture to minimize the discomfort and physical strain resulting from, for instance, head movement required to view the displays. The Military Standard (MIL STD) 1472 F (US Department of Defense, 1999) includes a range of guidelines on large screen display setups.

Collaborative work requirements deal with the form of displayed information. A common misunderstanding is that the use of shared displays will automatically enhance team collaboration. In reality, a poorly configured knowledge wall can distract and even confuse operators. A properly configured display should be based on both operational requirements and information priority. Researchers are generally in favour of using shared displays for presenting tailored information, rather than for simply projecting individual displays (Vernik, 2006). In all three studies, the following questions were used to guide the design:

- What kind of shared information needs to be presented on an off-workstation display?
- How should such information be presented?
- When multiple off-workstation displays are used, how does one coordinate the presentation across the display array?

In the case of a large-scale joint command centre, e.g., the ICC, it is common to set up wall-sized display arrays. Such a display can be configured to present multiple threads of feed which are used by subgroups within the centre. In order to properly formulate the subgroups, a clustering analysis was conducted to group the operators into teams. Resultant informational requirements were then used to configure the display array. In addition, when large off-workstation displays are used, the relevant environmental setting (e.g., lighting) within a command centre should be specified according to existing standards. More detailed discussions on off-workstation display setup in a command centre environment are available in Gouin (2007).

3.4.4 Environmental requirements

In all three recent studies, the designed command centre resided in existing office buildings. Their environmental requirements were not considered to be different from those of a regular office environment. Therefore, the workspace solutions essentially cited the environmental specifications (e.g., the thermal conditions, air quality, lighting, and acoustics characteristics) from existing industrial standards, e.g., ISO 11064. Although it is an important aspect of workspace design, the environmental specifications represented a small amount of effort in all three studies.

3.5 Other Project Practicalities

In addition to these aforementioned design considerations, two practical issues were repeatedly encountered in the JCWA studies. Although these issues did not directly affect the workspace solutions, they did influence the selection of analytic methods and design procedures.

The first one was the lack of access to SMEs. This issue arose from two different causes: (1) the SMEs had relevant information but were too busy. This occurred in both the JTF(E) and GJOC studies. (2) there was no expert to provide the information. For example, at the time when the ICC study was conducted, there were no SMEs to provide information about detailed operational tasks. In either case, the availability of SMEs was an issue.

The second issue was a tight timeline. In all three studies, the workspace design was a component of a larger effort to construct a command centre. It was executed in parallel to other project initiatives, e.g., IT infrastructure development, personnel training. The workspace design often required output from, or provided input to, the parallel initiatives. Very often, the analysis and design were conducted in a limited time and prompt responses on workspace decisions were required.

To deal with these challenges, a number of choices were made in the workspace design process. A goal-oriented method was used for operational analysis, as opposed to a solely task-based one. Layout software support tools were used. Finally, the design procedure was streamlined and tailored according to clients' expectations. The next section will provide an in-depth description of the elements of the tailored design process.

4 A-WAND: An Alternative Workspace Analysis and Design Process

This section describes the workspace analysis and design process, A-WAND, created and applied in the JCWA studies. The new process was modified from the recommendations in ISO 11064. The aim of the modification was to accommodate the command centre's unique operational requirements and the project practicalities described in the previous section. A-WAND emphasizes capturing operators' information requirements and communication needs, and it also maximizes the use of analytical methods and design tools developed by DRDC Toronto. Section 4.1 explains the tailored design process. Section 4.2 highlights the key methods and tools incorporated in the procedure.

4.1 A Streamlined Design Process

As an alternative workspace analysis and design method, A-WAND follows user-centred design principles and represents a top-down approach towards workspace analysis and design. Compared with the design procedures described in Section 2, a key improvement is the use of operator task information as a common driver for both workstation and layout designs. As a result, A-WAND integrates design procedures for both elements into a single process. According to A-WAND, the design of workstations and layouts are driven by two different types of operator tasks. *Task work*, which refers to tasks that are carried out by each operator independently, dictates how a workstation should be configured. *Teamwork*, which includes tasks that require collaboration among a team of operators, is used to determine communication links and ultimately, the room layout. The integrated procedure streamlines the design procedure and enables analysts to generate workspace solution more quickly to fulfill project timeline requirements. Teamwork requirements, in principle, also should be considered in the workstation setup. However, due to the use of a baseline workstation (as described in Section 3), the impact of communication needs on workstation design was regarded as minimal and was not considered in three studies. Such omission would not be appropriate if a specialised work console was to be developed.

A-WAND consists of five distinct phases, depicted in Figure 5. The initial phase involves collecting basic data about a joint command centre (e.g., mission and operation requirements, manning level, operator roles and responsibilities, physical constraints). The required data are collected through SME interviews or focus groups. These data are then fed into the second analysis phase where HGA is conducted. HGA output, particularly the low level sub-goals, is used to elicit user task information. The workstation and layout solutions are then generated based on both the task requirement and the ergonomic data obtained from the target user population. In a typical project, a number of design solutions are created. The solutions are evaluated in the fourth phase. A battery of assessment methods can be applied, including computer-based simulations, subjective user assessment, and human-in-the-loop experiments. The pros and cons of each workspace solution are documented and submitted for client decision-making. The process is iterative, and feedback from the evaluation can be used to further adjust the designs.

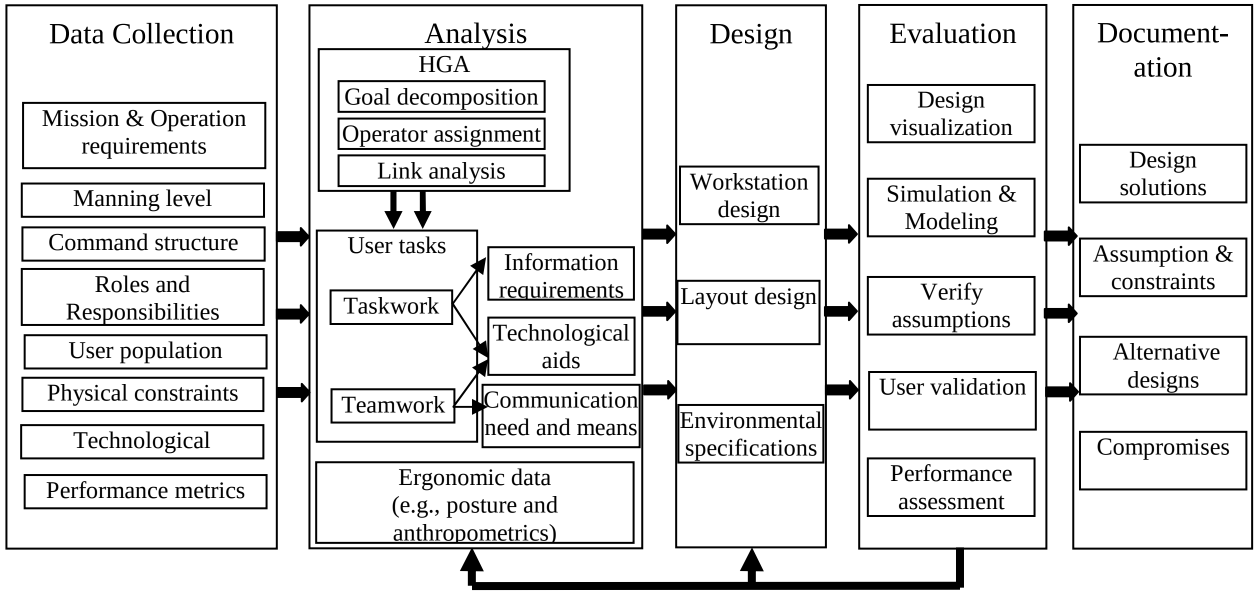

Figure 5. *An illustration of an Alternative Workspace ANalysis and Design (A-WAND) process.*

4.2 Key Analytical Methods and Tools

While many elementary procedures in A-WAND are consistent with the ones suggested in ISO 11064, three design activities were modified significantly. They reflect the tailoring effort made by the project team. A detailed account is provided in the following sub-sections.

4.2.1 Hierarchical Goal Analysis (HGA) and its extension

The first modification is the use of hierarchical goal analysis (HGA) in conjunction with task analysis. Although task requirements remain a key enabler for both workstation and layout designs, HGA provides a framework for capturing a wider spectrum of user requirements in support of process mapping and the identification of communication needs.

In a nutshell, HGA is an analytical framework for interpreting the goal-oriented behaviour of an individual or an organization (Chow et al., 2006). One core assumption of HGA is that the behaviour of an organization or an individual is goal-driven. Goals are represented in a hierarchical form, with high-level goals supported by lower-level sub-goals (Hendy, Beevis, Lichacz, & Edwards, 2002). The objective of applying HGA in workspace designs is to use it as a guiding framework for examining operator work requirements, not to interpret human behaviour. As a result, additional goal attributes and analysis steps were introduced to augment conventional HGA.

There are two reasons behind the decision to adopt HGA. First, the JCWA studies showed that the goal hierarchy (especially at the highest levels) of a command centre is consistent and robust across the various military command centres. This enables analysts to reuse HGA output from previous studies. In the GJOC design, for example, HGA output from the previous JTF(E) study was treated as a base template, and this saved significant SME time during the initial data collection. Second, the use of HGA is effective in cases where operator tasks were not fully defined. In the ICC study, a conventional task analysis was difficult to perform since details of inter-operator collaboration were not available at the time when the study was conducted. HGA provided a useful alternative by allowing analysts to derive task information based on decomposed operators' goals.

A conventional HGA involves three steps: goal hierarchy generation, operator allocation, and internal variable assignment.

The first step starts with an identification of the highest-level goals of an organization, in this case, a joint command centre. Then, these high-level goals are decomposed into sub-goals. For example, in GJOC, a single level-one goal was identified as "support RCMP in the Van2010 integrated security operation". To achieve this goal, five level-two objectives were identified, ranging from "Maintain maximum situational awareness", "Provide integrated planning support", to "Provide command and control when CF assistance is required". Each of these level-two goals was also further decomposed into its respective supportive goals. This process is performed iteratively and stops at a level that is sufficient to address the research questions. In some cases, the process stops when the goal can be fulfilled by an individual operator. By the end, a goal hierarchy is created. As an example, Figure 6 shows a portion of the goal hierarchy produced for GJOC.

The second step is to assign operators to each goal. The operators are responsible for the delivery of a goal, and should be accountable when the goal is not achieved. The information is important for identifying issues like overlapping roles and responsibilities within an organization. HGA typically assigns a single operator to each goal based on the argument that this individual (e.g., manager, commander) is accountable, even though a team of operators supports the goal. For workspace analysis, the assignment of multiple operators to a single goal was allowed and the intent was to support the communication modelling performed at a later stage of analysis.

The third step is to allocate an internal variable to each of these goals. This variable serves as a set point for a goal and can be used for measuring the goal's completeness. Mapping out the variables across the entire goal hierarchy allows analysts to diagnose potential instability issues. For instance, if a variable is influenced by multiple goals, and thus multiple processes, it can lead to potential instability and clarification or redesign is necessary.

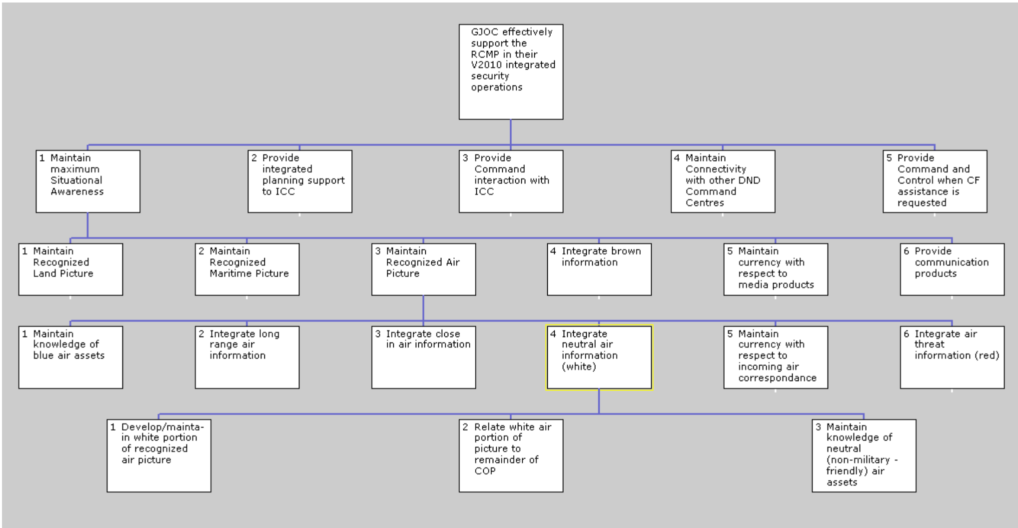

Figure 6*. A sample HGA output from the GJOC study*
(Adopted from Coates & Perlin (2009)).

The preceding three steps reflect the procedure followed in a conventional HGA. To support workspace design, A-WAND augments HGA with three further steps: the identification of communication requirement, an input/output interface specification, and a goal importance rating.

The fourth step specifies communication requirements associated with each goal. For workspace design, communication is defined broadly to include both inter-operator exchanges and information acquisition from technological devices (e.g., shared displays). In three studies, seven communication types were defined (sidebar, direct, visual, auditory, discuss, collaborate, and accessibility). The distinction among these different communication types is based on the modality of exchange and the nature of inter-operator interaction. Each type has a different implication for workspace requirement. For example, ‘supervise’ and ‘sidebar’ are regarded as different types of communication. While both require direct face-to-face conversation, ‘supervise’ also implies that the supervisor needs direct visual access to the supervised operator’s workspace. More details about these communication types can be found in Coates & Perlin (2009). A sample output from this analysis is shown in Figure 7.

The fifth step identifies the medium of communication which consists of the input and output interfaces, such as email, telephone, chat room, or face-to-face conversations. The information is used to elicit the adjacency requirements in a layout design.

The last step involves rating the importance of each goal. A five-point Likert scale is used, ranging from ‘not important’ (1) to ‘critical’ (5). In Figure 7, the importance rating for Goal 1.3 “Maintain recognized air picture” was 4. Together with a separate rating on link importance, the goal rating is applied in an algorithm for computing the importance weightings for each communication link.

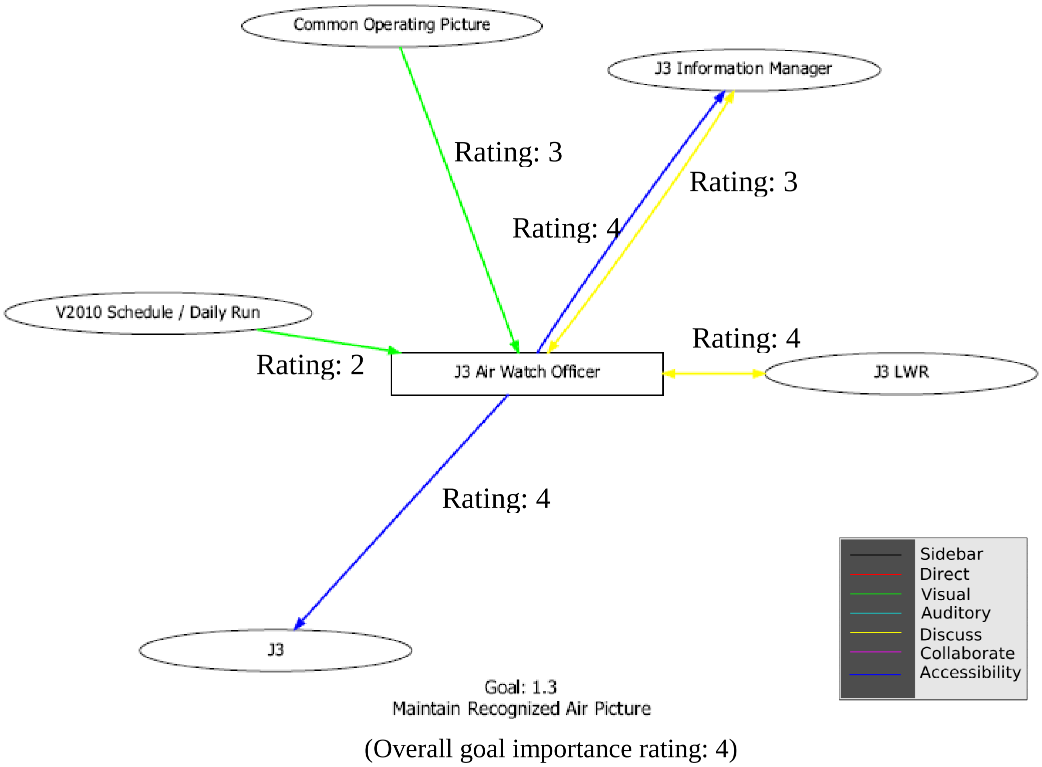

Figure 7. *An example of communication requirement analysis conducted in HGA. In this case, the J3 Air Watch Officer is assigned to Goal 1.3 (Maintain recognized air picture). To support this goal, J3 Air requires (1) direct visual to both 'common operating picture' and 'Van2010 Schedule/Daily Run'; (2) group discussion with J3 Lower (LWR) and J3 Information Manager; and (3) easy access to J3 and J3 Information Manager. The overall importance rating of this goal is 4 (out of 5), and the ratings for each communication link are specified in the diagram. (Adopted from Coates, Perlin, & Stewart (2009)).*

HGA data are collated in Task Architect®, a software tool that provides a convenient platform for recording HGA data and visualising associative relationships. As revealed in past projects, SMEs appreciated the ability to view the HGA data from two perspectives: a conventional view of the goal hierarchy (e.g., Figure 6) provided SMEs with a holistic sense of mission objectives and requirements, and an operator-centric view (e.g., Figure 7) allowed SMEs to diagnose the goals linked to each individual. This ability was later also found to be very useful in verifying and validating both the raw data and the design assumptions.

4.2.2 Modelling of communication

The room layout of a joint command centre is determined by operators' teamwork requirement, which is reflected in turn by their communication needs. Specifically, the inter-operator communication links, including its type, frequency, and priority, are used to determine the adjacency requirement in a layout solution. As mentioned previously, communication was defined loosely in the JCWA studies to include not only inter-operator information exchanges, but also an operator's access to common data sources, such as the COP.

Networked computers and collaborative software enable operators to work together and communicate remotely through emails or chat rooms. Since this form of communication is not affected by physical proximity among operators, it was not regarded as a layout driver and thus was not captured in the communication model. The data, however, were recorded for other operations analysis, like process mapping. As a result, the modelling effort focused on communication types where the human's perceptual capability (e.g., visual and auditory) was a limiting factor and technology did not aid the information exchange. Note conventional layout design guidelines (e.g., the one proposed by ISO 11064) do not explicitly emphasize communication analysis. Therefore, instructions on communication modeling are not provided in these guidelines. The approach described below represents a modeling solution uniquely adopted by A-WAND.

In the JTF(E) study, four communication types were analyzed (sidebar, visual, auditory, and direct). Three additional types were included for the ICC and GJOC studies (discuss, collaborate and accessibility). The following heuristics were used to distinguish the communication types:

- Sidebar: one-on-one discussions, without disturbing other operators
- Direct: provision of direction
- Visual: visually monitor shared display(s)
- Discuss: group discussion with multiple operators
- Supervise: provision of supervision, particularly, the supervisor needs to see what another operator is doing, may have to see the other operator's display
- Collaborate: sidebar with more than one operator
- Accessibility: ability to leave the work area and access another operator or entrances or exits.

This classification is not based solely on communication modality. Rather, it considers both the modality and purpose of information exchange. Some communication types incorporate multiple modals of operation, for example, *supervise* has both a verbal and a visual component.

For each type of communication, two mathematical functions describe the source and receiver functions, respectively. Together they determine the deterioration of communication effectiveness based on both the distance and the spatial relationship between the communicators. A detailed description is available in Coates and Perlin (2006).

The communication data are captured in HGA, with the type of communication links identified as a goal attribute. Once the entire goal hierarchy is created, the HGA output can be presented in an egocentric perspective, as illustrated in Figure 7. An importance rating for each communication

link on a five-point Likert scale is then performed. This rating represents a local prioritization by each operator. Together with the goal importance rating, which is based on a global prioritization captured in HGA, the product of these two ratings reflects the overall importance of a communication link. This value is applied in the computation of a layout's cost functions (e.g., figure-of-merit scores).

4.2.3 Specialised workspace design software

Two layout software tools were used and tested, LOCATE and VNCEP. Both are human-systems integration (HSI) tools developed by DRDC Toronto. Compared with other commercially off-the-shelf (COTS) layout toolkits, e.g., Microsoft Visio and the Computer Aided Design (CAD) family of software, LOCATE and VNCEP not only support layout rendering, but also incorporate human factors design principles for assessing and optimising layout solutions. For example, both possess internal constructs for modelling communication requirements and both adopt the mathematical cost model devised by Hendy (1984, 1989). Consequently, they were the preferred design platforms adopted in recent projects.

LOCATE is a specialized software package for analyzing and optimizing workspace layouts, with an objective to improve communication among operators and machines. It consists of a full-featured graphical interface for workspace design. It can model and assess communication in various forms, including visual, auditory, tactile (or reach) and distance (or movement). A unique strength of LOCATE is its ability to compare ratings for a variety of candidate layouts and rearrange a layout automatically based on an internal cost function. Besides the JTF(E) study, LOCATE was also used to design the operations room for the US Navy surface combatant-21 project (Edwards, 1999; Hendy, Berger, & Wong, 1989).

VNCEP was originally developed as a generic three-dimensional (3D) visualization tool. Its primary purpose was to support fast 3D prototyping and versatile visualization. The software was later further developed to incorporate Hendy's algorithms for handling workspace cost functions. It was used for layout designs in both the GJOC and the ICC studies.

The strength of VNCEP lies in its capability to deal with workspace modelling in three dimensions and its support of flexible re-programming. The use of 3D data allows analysts to examine large screen displays and address operators' proper visual angles in a room layout. It has no limitation on the number of communication channels that can be modelled. As an open platform, much of the layout cost computation is achieved by programming using a scripting language. In addition, VNCEP provides an easy-to-use interface for interacting with the virtual workspace model. It is possible, for example, to specify a viewpoint anywhere in the virtual space and create an immersed view. This was found to be very useful in the ICC study during layout validation with SMEs.

Limitations of both tools were revealed in the design process. Their resolution are proposed and discussed in Section 5.2.4.

5 Future Research and Development Roadmap

A-WAND was successfully applied in the JTF(E), the GJOC and the ICC studies. Following the streamlined design procedure, workspace solutions were generated in a timely fashion and were later implemented in the designated command centre. However, this process is not without problems and a number of issues were revealed in these studies. This section starts with a quick summary of the identified issues and then describes the future R&D effort required to advance DRDC's capability.

5.1 Unresolved Issues

Three issues were identified in the recent studies.

First, assumptions adopted in A-WAND need to be validated. One example is the parameter setup for the source and receiver functions used in communication modelling. The current values were obtained from a small set of SMEs, and for particular operational settings. The generalizablility of these functions to a wider range of operations has yet to be verified. Another example is the accessibility attribute collected in HGA. Two empirically defined thresholds were adopted (20 and 60 feet). The proximity between two operators influenced their ability and willingness to conduct direct face-to-face conversation. According to the current thresholds, if the inter-operator distance was less than 20 feet, then accessibility was considered desirable and the separation was assumed to allow the operators to walk to each other's desk and collaborate frequently; if the inter-operator distance was between 20 and 60 feet, the separation was regarded as acceptable to support infrequent or non-routine requirements for face-to-face communication; the accessibility became poor if the inter-operator distance was greater than 60 feet, the assumption was that operators did not interact face-to-face. These thresholds were estimates obtained from SMEs. Verification of their validity and applicability to other types of command centres is required.

Second, several software tools were suggested in A-WAND to support the data collection, analysis, and workspace design. However, these tools were not fully integrated. Specifically, Task Architect® was used for capturing HGA data and visualizing its output, while LOCATE and VNCEP were used for layout design. Although HGA outputs were used to drive the layout design, these tools did not share data and the processes were not integrated. In other words, data analysis and layout design were performed independently. Changes in HGA had to be manually fed into the layout software. This had increased the work effort, and the process was error-prone.

A further integration is needed to improve the interoperability across toolkits. One solution is to adopt a common data format to support data sharing. Another is to focus on process integration and create a front-end module in either LOCATE or VNCEP for processing HGA. The goal is to connect HGA data directly to the layout generation engine and all information related to a workspace layout is treated as a single data set. As a result, any modification of HGA output will be automatically reflected in the layout design and cost functions.

Third, the design procedures adopted by A-WAND currently are biased toward the static arrangement of workstations. One implicit expectation is that operators will sit at their console

while performing their tasks. The existing communication models used in LOCATE and VNCEP both compute the communication cost based on this assumption. However, the assumption's validity is seriously challenged in a joint command centre. For example, in the theatre command centre (within the ICC), key personnel (e.g., senior watch officer) need to walk around the centre frequently and much of their work was conducted outside of their designated workstation. This requirement reflects a dynamic aspect of a command centre's operation, which has yet to be resolved in A-WAND.

The fluctuation of operator mental workload also reflects operational dynamics. Since workload can be affected by workspace layout and has potential influence on operator performance, it is useful to include the workload factor in the layout evaluation metrics.

The resolution of these issues requires both development effort and future research. In the rest of this section, an R&D roadmap is proposed, focusing on advanced analytical methods, tool development, and process integration.

5.2 An R&D Roadmap

The workspace solutions, particularly for GJOC and ICC, were tested extensively after implementation. The feedback led to subsequent layout modifications. Some adjustments were made due to the availability of new data. For example, for the ICC the establishment of SOPs for inter-agency collaboration superseded many assumptions used in the initial layout design. Other modifications were attributed to the analytical methods and evaluation metrics adopted in A-WAND. As pointed out in the previous sub-section, the analysis and design method adopted in A-WAND can primarily be regarded as static. Collected data (e.g., SOPs) represent a static view of a command centre's operations; the analytical methods emphasize prescribed tasks, and the evaluation assumes operators function behind their consoles. As a result, the workspace solutions required changes when exposed to real life actions. This, by itself, is not a serious criticism of A-WAND. It is unreasonable to expect a design process to generate a 'perfect' solution that has considered all possible operational deviations. However, an enhancement of the current process will allow analysts to generate more robust solutions. This objective can arguably be achieved by adopting the analytical frameworks described in the following sections.

5.2.1 Social network analysis

The recent studies have proven the usefulness of adopting a goal-based analytical method in conjunction with a conventional task analysis for examining a command centre's operation (Coates & Perlin, 2006; Coates, Perlin, & Stewart, 2009; Coates & Perlin, 2009). Outputs captured by these methods represent a 'formal' or 'prescribed' way of operation. In other words, the output is consistent with the goals, tasks, and interactions specified in a command centre's CONOPS or SOPs. However, operators do not always follow prescribed procedures and it is commonly observed that operators interact through *informal networks* within an organization (Krackhardt & Hanson, 1997). Details of such informal behaviour can only be obtained by observing real operators engaged in real life actions. Such informal interaction should be captured and analyzed for workspace design, either to encourage or to discourage such behaviour.

One promising analytical framework to address this issue is the social network analysis (SNA). Based on network theory, SNA has sociological roots. It is an effective method for studying communication patterns (Freeman, 2004). In both GJOC and ICC studies, after the recommended workspace solutions were implemented, tests and exercises were conducted. Operational data were collected, including inter-operator information exchanges like direct conversation, email or chat room exchanges. These data could be analyzed using a social network framework in which individual operators could be represented as nodes and the communication links as connectors between nodes. By mapping both the type and frequency of communication onto the network, a realistic mapping of inter-operator interaction could be created, which might deviate from the ones specified in the SOPs. In this sense, SNA is complementary to existing methods and provides an alternative for modelling communication in a command centre. Its integration into A-WAND should allow analysts to optimize designs and generate robust workspace solutions.

5.2.2 Cognitive work analysis

The design process suggested by A-WAND, i.e., Figure 5, emphasizes the use of task data for deriving both workstation and layout solutions. The task information is therefore critical to the design process. Following the current analysis procedure, this information is obtained from SOPs or from SMEs who (in most cases) relay information from SOPs. While such task data will capture the skill-based or rule-based operator behaviour, they are less acceptable for describing operator's knowledge-based behaviour, e.g., course-of-actions taken when handling novel situations (Rasmussen, 1986). Often these novel situations represent challenges to a command centre's operational capability, and a command centre should be designed with a capacity to handle 'surprises'. It is therefore important to capture the knowledge-based behaviour in task data while conducting workspace analysis.

Cognitive work analysis (CWA) provides a promising framework for fulfilling this requirement. As a multi-phased analytical framework for representing the structural, cognitive, and social constraints on work in a sociotechnical system (Vicente, 1999), CWA attempts to guide system designs by identifying the intrinsic constraints imposed on operators' work. By focusing on the constraints, CWA promotes solutions to enhance operators' adaptability to unexpected and changing work demands.

The current workspace analysis has considered the physical limitations of a command centre. By applying CWA, it is possible to incorporate work-related constraints in a solution. In principle, workspace designs generated on a constraint-based approach better satisfy dynamic operational requirements. Details about CWA are beyond the scope of the current report. Vicente (1999) and Lintern (2009) provide more information.

5.2.3 Cognitive workload assessment

The ultimate measure of a command centre's effectiveness is its operational performance, which depends on the collective performance of all operators. In a typical command centre, operators' tasks involve both constant situational monitoring and a reactive response to any incident. The nature of their tasks makes them susceptible to two extreme states of cognitive demand: a prolonged period of monitoring task increases the risk of reduced vigilance, whereas a rapidly

escalating incident can lead to potential overloading. Both states are detrimental to operator performance and should be avoided.

The solution depends upon operators' responsibility assignment and the overall manning scheme. In the context of this report, a workspace solution can also play a useful role. During the workspace design, an operator's task information can be used to construct a human performance model. The model can be used to estimate an operator's cognitive task demand and diagnose potential operator performance breakdown. For example, the room layout solution can be used to evaluate operators' physical effort when they move around in the command centre.

There are existing human performance modelling tools, such as the integrated performance modelling environment (IPME), which can be applied in this context. IPME is a modelling environment for simulating human behaviour and assessing human-system performance (Dahn & Laughery, 1997; Hendy & Farrell, 1997). Based on a discrete-event simulation engine, IPME uses an interconnected network of tasks to represent human activities. Performance outputs, including operator workload, can be used as a basis for evaluating system design, in this case the workspace layout.

Operational scenarios can be created within an IPME model, which enables analysts to examine the model under various hypothetical conditions. By linking the model to the workspace solution, it becomes possible to evaluate the effectiveness of the room layout under more realistic and dynamic conditions.

IPME is capable of supporting data exchange with other models, although LOCATE and VNCEP do not support this. To facilitate model integration, further development in layout software is needed. The development will focus on an interface capable of: (1) sending 3D coordinates for both workstations and operators to other models (e.g., IPME); (2) receiving 3D operator coordinates from other models; (3) updating the computation of cost functions or figure-of-merit in the layout software. Besides these core capabilities, improved visualisation that dynamically depicts an operator's disposition will also improve the overall usability of the models.

5.2.4 Layout design software

Both LOCATE and VNCEP revealed weaknesses, as discussed in Section 4.2.3. Their required treatments differ.

LOCATE supports two dimensional (2D) layouts and its internal data structure does not handle the third dimension. This is a limiting factor, as it prevents the computation of vertical visual angles necessary for configuring large common displays. The issue becomes more pronounced for command centre designs given the extensive use of shared displays. In addition, visualization in LOCATE is only available through a 2D top-down view. As revealed in the GJOC and ICC studies, an ability to survey the workspace from various vantage points is helpful for design evaluation. Such capability should be incorporated into LOCATE.

Second, internal constructs in LOCATE allow analysts to examine four different communication channels. These channels can be customised to represent additional communication types (i.e., other than the four default types: visual, auditory, touch and distance). However, when more than

four communication types must be modelled, the software cannot accommodate the analysis requirement. Further development is needed to remove this constraint.

VNCEP, as a generic visualization platform, is flexible enough to be configured to handle workspace design tasks. However, the capability currently resides only in its development team. The lack of sufficient technical documentation also creates barriers for wider use. There are several program scripts produced for supporting layout analysis: for example, the calculation of figure-of-merit for each layout. It is useful to incorporate such functions into VNCEP.

One solution is to create a layout toolbox. This would allow the basic VNCEP module to be used in its conventional way for supporting 3D modelling and visualization. At the same time, the layout toolbox can process workspace related parameters and algorithms, including the HGA data, communication models, and figure-of-merit algorithms.

VNCEP lacks an internal optimizer, unlike LOCATE. VNCEP can be programmed to compute a cost rating (e.g., figure-of-merit score) for a particular layout, and this score allows analysts to compare different solutions. However, VNCEP cannot diagnose the bottlenecks in a design, or recommend an improvement based on these scores. This becomes important for the design of large floor plans where complex interactive relations exist among a large number of operators and equipment. An internal optimising function which ranks these relations and automatically adjusts layout arrangement based on the ranks would significantly reduce the re-design effort.

5.3 Final remark

The main objective of the above R&D solutions is to formulate an integrated workspace design process. This process consists of analytical modules to be applied in a plug-and-play fashion depending on the design requirement and the nature of the command centre. It is apparent that the R&D solutions proposed (e.g., SNA, CWA) are also applicable to other design challenges. Rather than creating an integrated platform capable of incorporating all these analytical frameworks, it is more sensible to develop an independent tool for each. The interoperability between these tools is enhanced by following service-oriented architecture.

The conventional design approaches, including A-WAND, focus mostly on the static aspect of a workspace and the R&D solutions proposed in Section 5 allow analysts to extend the analysis into the dynamic domain. However, none of the methods include the social aspect of a workspace solution. A command centre is a space where work is conducted, and a social bond is cultivated. A workspace designer should be interested in the *water cooler effect*, where a shared facility plays an important role in shaping information distribution (e.g., office rumours). With the setup of large joint command centres and the increase of staff members, the social impact of rest areas and shared facilities becomes more important and should be considered in the workspace solution. Appropriate analysis methods have yet to be developed.

Another trend in a command centre setup is the increased reliance on telecommunication technologies. Networked computers and collaborative software have affected workspace layouts. In the future, virtual command centres will be created where operators can collaborate remotely. A tele-conferencing facility was already included in the ICC. With the further advancement in virtual reality and tele-presence applications, it may be possible to remove the proximity

constraints that are encountered in the current workspace design. The ergonomic analysis, as a result, will focus more on human-computer interaction issues.

In summary, this report proposed a new workspace design process A-WAND, created and continually developed in three recent projects. A-WAND streamlines the design procedures recommended by existing industrial standards. It incorporates tools and methods that have been previously developed by DRDC and was tailored to support the design of joint command centres. Limitations of this workspace design process were discussed and an R&D roadmap sheds light on how DRDC's HSI capability in this area could be advanced.

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List of symbols/abbreviations/acronyms/initialisms

2D	Two dimensional
3D	Three dimensional
A-WAND	Alternative method for Workspace ANalysis and Design
ASOCC	Air Security Operations Coordination Centre
CF	Canadian Forces
CONOPS	Concept of operations
COP	Common operating picture
COTS	Commercial off the shelf
CWA	Cognitive work analysis
DND	Department of National Defence
DRDC	Defence Research and Development Canada
GJOC	JTF(Games) Joint Operations Centre
HGA	Hierarchical goal analysis
HSI	Human systems integration
ICC	Integrated Command Centre
IPME	Integrated performance modelling environment
ISO	International Organization for Standardization
IT	Information technology
J3 LWR	J3 Lower
JCC	Joint command centre
JCWA	Joint command workspace analysis
JIMP	Joint, inter-agency, multi-national, public
JTF(E)	Joint Task Force (East)
JTF(G)	Joint Task Force (Games)
MIL-STD	Military Standard
OMOC	Olympic Marine Operations Centre
R&D	Research and development
RCMP	Royal Canadian Mounted Police
S&T	Science and technology
SME	Subject Matter Expert

SNA	Social network analysis
SOP	Standard operating procedure
TCC	Theatre Command Centre
TS	Top secret
VACC	Vancouver Area Command Centre
VNCEP	Virtual Navigation and Collaborative Experimentation Platform
VOIP	Voice-over-IP
WACC	Whistler Area Command Centre

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3. TITLE (The complete document title as indicated on the title page. Its classification is indicated by the appropriate abbreviation (S, C, R, or U) in parenthesis at the end of the title)

Joint command support through workspace analysis, design and optimization (U) (U)

4. AUTHORS (First name, middle initial and last name. If military, show rank, e.g. Maj. John E. Doe.)

Wenbi Wang

5. DATE OF PUBLICATION (Month and year of publication of document.) October 2009	6a NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.) 48	6b. NO. OF REFS (Total cited in document.) 23

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of document, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

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10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document) DRDC Toronto 2009−100	10b. OTHER DOCUMENT NO(s). (Any other numbers under which may be assigned this document either by the originator or by the sponsor.)

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(U) The current Canadian Forces (CF) transformation focuses on network enabled capabilities and promotes joint operations both within the CF and under a broad joint, inter−agency, multi−national, public (JIMP) paradigm. The past a few years have witnessed an increased demand on the science and technology (S&T) support for performing ergonomic analysis and workspace design for joint operations centres. A series of studies have been conducted from 2006 to 2008 in which workspace solutions were produced for three different joint command centres. In these studies, a new design process, Alternative method for Workspace ANalysis and Design (A−WAND), was proposed and then further developed. A−WAND is based on integrating and streamlining existing design procedures recommended in industrial standards and is tailored to support unique operational requirements of a CF joint command centre. In addition, it emphasizes the use of analytical methods and software tools that have been developed, and therefore possessed, by Defence Research and Development Canada (DRDC). This report describes A−WAND, documents the best design practises, and discusses future research and development (R&D) efforts that are needed to further advance DRDC's capability in this area.

(U) La transformation actuelle des Forces canadiennes (FC) porte sur des opérations facilitées par réseaux et fait la promotion des opérations interarmées à la fois au sein des FC et dans le cadre d'un paradigme interarmées, interorganisationnel, multinational et public (IIMP). Au cours des dernières années, on a constaté une augmentation de la demande sur le soutien des sciences et de la technologie (S & T) pour effectuer une analyse ergonomique et la conception de l'espace de travail pour les centres d'opérations interarmées. Une série d'études a été menée de 2006 et 2008 dans le cadre desquelles des solutions liées à l'espace de travail ont été mises au point pour trois centres de commandement interarmées. Dans ces études, un nouveau processus de conception, une méthode alternative pour l'analyse et la conception du milieu de travail (A−WAND), a été proposé puis développé de façon plus approfondie. L'A−WAND est fondée sur l'intégration et la simplification des procédures de conception existantes recommandées dans des normes industrielles et est adaptée pour soutenir les exigences opérationnelles uniques d'un centre de commandement interarmées des FC. De plus, elle met l'accent sur l'utilisation de méthodes analytiques et d'outils logiciels qui ont été mis au point et, par conséquent, ont été possédés par Recherche et développement pour la défense Canada (RDDC). Le présent rapport décrit l'A−WAND, rend compte des meilleures pratiques de conception et discute des futurs efforts de recherche et développement nécessaires pour faire progresser la capacité de RDDC dans ce domaine.

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(U) Workspace design, ergnomic analysis, layout design

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